The influence of bedrock topography on the dynamics of two clayey landslides in the Trièves (French Alps)

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ABSTRACT: The two large adjacent landslides of Avignonet and Harmalière, affecting thick clayey quaternary deposits, are located in the Trièves area (French Alps). Remote techniques (Lidar) and GPS measurements were used to characterize the two landslides. Results show major differences between the dynamics of the two landslides, both in morphology, displacement rate magnitudes and motion directions. Seismic noise measurements (H/V technique) were performed to map the clay layer thickness. Combined with Lidar derived DEM, these data yielded the paleo-topography of the seismic substratum made of compact alluvial layers and Mesozoic bedrock. The difference in dynamics between the two landslides is likely to result from the presence of a ridge of compact formations at the Avignonet landslide toe, preventing an eastward deep active sliding to develop and explaining the observed shallow slip surfaces. To the South, this buttress disappears at the Harmalière toe, favoring a deep sliding in a Southeastern direction with a fast regression of the headscarp, which evolves into a mudslide at its base.

1 INTRODUCTION

The Trièves is a depression area within the French alpine foreland, located at about 40km south of Grenoble. This 300km^2 large area is covered by a thick Quaternary clay layer (up to 200 m), which was deposited in a glacially dammed lake during the Würm period (Monjuvent 1973). After the glacier melting, rivers have deeply incised the geological formations triggering numerous landslides. The two studied adjacent landslides Avignonet and Harmalière are situated along the west shore of the lake Monteynard (Fig. 1). The clay layers have covered a paleo-topography made of Jurassic limestones and overlying compacted old alluvial layers located along paleo-valleys of the river Drac. This results in an irregular surface of the base of the clay deposits.

In March 1981 the Harmalière landslide was triggered after a heavy rainfall provoking the melting of the snow cover (Moulin & Robert 2004). This slide, which affected a surface of about 450,000 m^2 and created a head scarp of 30 m high, evolved into quick mudflow, which reached the lake. No such dramatic effects were observed for the Avignonet landslide but significant signs of instability were noticed during housing development (Lorier & Desvarreux 2004), triggering geotechnical and geodetic investigation campaigns. Slide velocity measurements at the surface and in boreholes pointed out that the maximum slide activity is located at the slide toe and is linked to a shallow active rupture surface at about

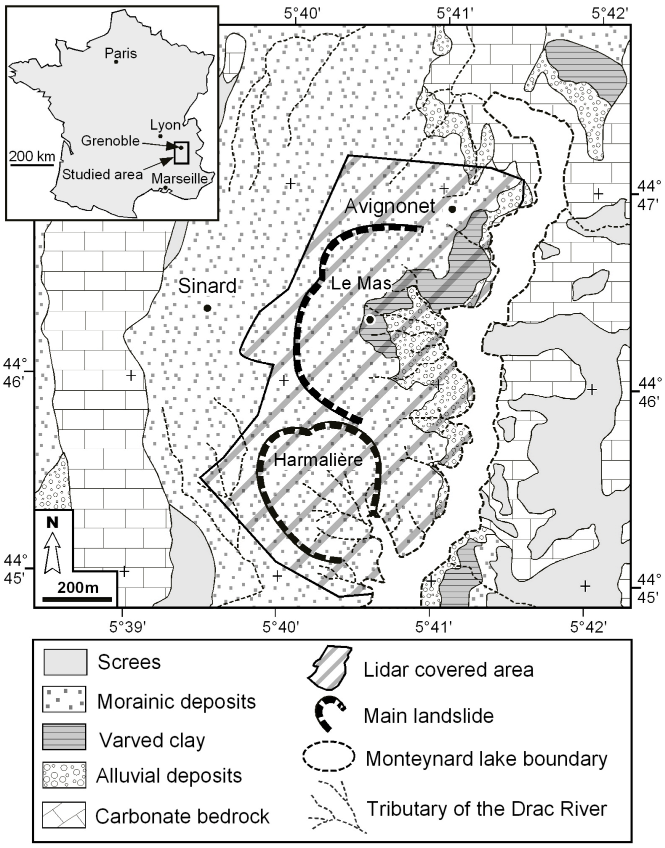

Figure 1. Geological map with the location of the Avignonet and Harmalière landslides and the area investigated by Lidar (Fig. 2).

13 m depth. These geodetic data are consistent with geomorphic observations (scarps, fissures, swampy

areas, bulges), which show an increase of the landslide activity downstream.

In order to understand the differences in the geometrical and dynamical characteristics of these two landslides, which occur on identical slopes made of the same geological, we performed a combined analysis of morphological, geodetic, geological and geophysical data.

2 LANDSLIDE DYNAMICS

2.1 *Morphological and geodetic data*

Three datasets are available to analyze the landslide dynamics of the two landslides: GPS measurements, aerial photographs and Lidar. GPS measurements have been performed biannually since 1995 by RTM (*Restauration des Terrains en Montagne*) at 25 points on the Avignonet landslide, relatively to several reference points located on nearby stable bedrock. No GPS measurements are available for the Harmalière landslide, owing to the quick surface evolution. The coordinate accuracy is better than 10 mm, allowing mm/y average velocities to be derived over the past 11 years.

Aerial photographs are available from IGN (*Institut Géographique National, France*) since 1948 with a periodicity of 8 years and a scale of about 1:30,000 (except in 1970, when the scale was 1:15,000). For this work, all photos were orthorectified, using the IGN DEM with a resolution of 50 m and ground control points measured with differential GPS.

A Lidar (LIght Detection And Ranging) laser scan, covering the Avignonet and Harmalière landslides (Fig. 1), was performed in November 2006 with the handheld airborne mapping system Helimap® (Vallet & Skaloud 2004). The resolution is about 30 cm with an accuracy of 10 cm in vertical and horizontal directions. The point cloud was filtered and interpolated to a 2m raster grid with the software SCOP++®, in order to derive the bare earth model excluding trees and houses (Fig. 2a). Shaded representations with different light angles were used for interpretation.

2.2 *Interpretation*

Several indicators were used to highlight the difference in dynamics between the Avignonet and Harmalière landslides: the general orientation of the landslide, the elevation profile, the surface velocity, the headscarp evolution and the surface roughness. While the Avignonet landslide moves eastward, down the general hill slope, the Harmalière slide runs out to SE (Fig. 2b). The elevation profile through Harmalière (Fig. 2c) is mainly concave, with a classical accumulation zone in the upper part and a sedimentation zone at the toe. On the contrary, the profile at Avignonet exhibits a global convex shape, owing to the presence of the rigid alluvial layers and the bedrock in the lower part.

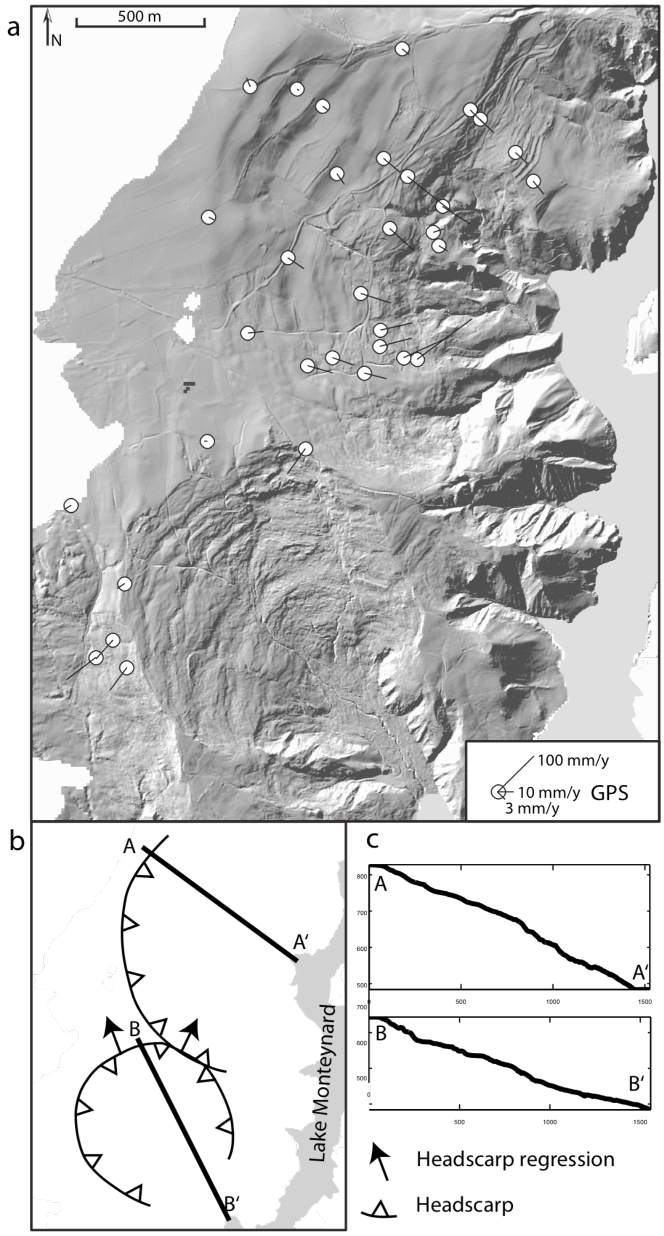

Figure 2. a) Shaded Lidar DEM with displacement vectors measured by GPS. b) Sketch of Fig.2a with the interpretation of the headscarps of the two landslides and location of the two profiles A' and BB'. c) elevation profiles of the two landslides.

The slide velocity values measured by GPS at the surface of the Avignonet landslide (Fig. 2c) vary from 0-2 cm/year at the top to more than 13 cm/year in the most active parts at the toe. The aerial photos show no major activity in Avignonet for the last 60 years, with no significant evolution of the headscarp. This is in agreement with the smooth topography shown by the Lidar DEM (Fig. 2c) in the upper part of Avignonet, which suggests the absence of fast recent movements. In Harmalière no GPS measurements are available but the aerial photos study yields an average velocity of several meters per year for the landslide body. The headscarp at Harmalière, which was created during the catastrophic event of March 1981 has regressed regularly, through several distinct events, at a mean rate of about 10 m/year (Moulin & Robert 2004). This evolution is traceable in the aerial photos and was dated by field observations (Moulin & Roberts 2004). Since 2001, the headscarp regression has started to affect the southern limit of the Avignonet landslide. This southward motion of the crest between the two landslides is also evinced by GPS measurements (Fig. 2a). The surface roughness observed in the Lidar DEM is an indicator for the landslide activity. It is much stronger and small-scale in the Harmalière landslide than in the Avignonet one. Only some areas in the lower part and in the South of Avignonet exhibit small-scale roughness. This is consistent with the location of exposed bare soil surfaces in the most recent aerial photos, which correlate to a higher landslide activity.

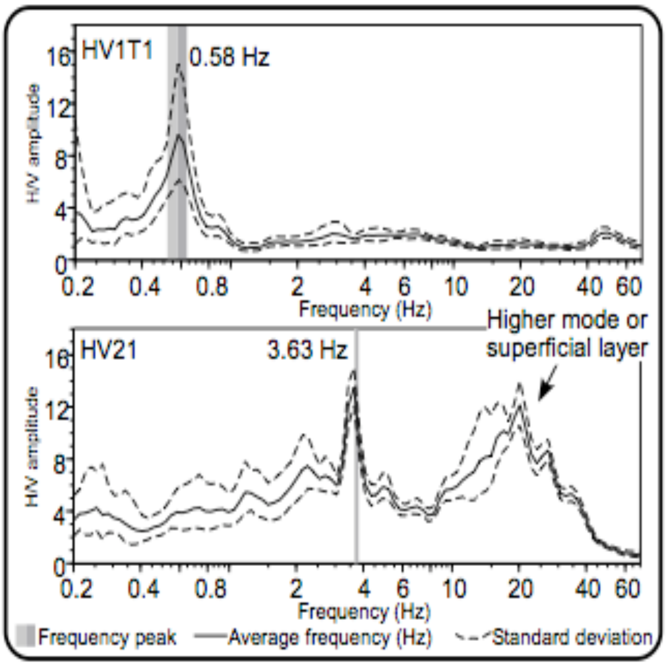

Figure 3. Spectral ratios (H/V) of ambient vibration measurements measured at the two points (HV21, HV1T1) shown in Figure 4.

3 BEDROCK TOPOGRAPHY

3.1 *Method*

Seismic noise measurements were conducted for determining the thickness of the clay layer overlying the seismic bedrock. The single station method (also called the H/V technique) was used at 78 locations (Fig. 4). It consists in calculating the horizontal to vertical spectral ratios (H/V) of seismic noise records and the resonance frequency of the soft layer generally appears as a peak on the H/V curve (Bard 1998). In cases with a high seismic impedance contrast between the soft layer and the bedrock, this H/V peak results in a change in the ellipticity of the fundamental mode of the Rayleigh waves (Bonnefoy-Claudet et al. 2006). For a single homogeneous soft layer overlying the bedrock, the resonance frequency is given by $f_0 = Vs/4H$ where Vs is the soft layer shear-wave velocity and H is the layer thickness. A low resonance frequency then corresponds to a thick soil layer and vice-versa. In the investigated area, the measured H/V curves exhibit peaks in a frequency range between 0.58 Hz and 3.63 Hz (see Fig. 3 for the H/V curves and Fig. 4 for measurement location).

In order to interpret the resonance frequency values measured on the H/V curves, we computed the fundamental ellipticity curves of Rayleigh waves and the corresponding theoretical resonance frequency values below each station. The dynamic characteristics (compressional wave velocity Vp, shear wave velocity Vs and density) within the different layers (moraine, clay, alluvium and bedrock) were obtained from a previous seismic study (Jongmans et al., in press). This computation was calibrated using the geotechnical cross-section P01 (Fig. 4), along which several boreholes were made and a detailed H/V profile was conducted. Theoretical and experimental values of the resonance frequency f_0 along this profile show a very good agreement, corroborating the determined velocity values in the layers. Sensitivity tests have shown that the main parameter controlling f_0 is the clay thickness. On the contrary, no change in the f_0 value has been found when passing the landslide headscarp. These results support the use of resonance frequency measurements for determining the clay thickness. The H/V deduced geometry for the seismic bedrock top was compared to a section previously established from a long refraction profile (Blanchet 1988) and depicting the top of the Jurassic bedrock. A general good agreement is observed between the two sections, the slight observed differences probably resulting from the presence of alluvial layers in-between the clays and the Jurassic limestones.

The thickness data obtained over the whole area were then subtracted from the Lidar DEM and were spatially interpolated (krigging with an exponential variogram model correction) to produce a topographical map depicting the bottom of the varved clays (Fig. 4).

3.2 *Paleo-topography analysis*

The map of Figure 4 reveals that the paleo-topography upon which clays were deposited was very irregular, with elevation variations more than 150 m. The major feature is the presence of a depression striking N-S, which is bordered to the East by a ridge culminating at an elevation of about 640 m. These results are consistent with existing geological data (Blanchet 1988; Lorier & Desvarreux 2004), which pointed out the westward increase of the clay thickness. This depression is probably a paleo-valley of the river Drac as suggested by alluvial outcrops along the lake. The NS ridge corresponds to the presence of carbonate bedrock covered with compact alluvial layers and sporadically outcropping along the lakeshore. To the South, this ridge abruptly disappears (Figure 4). In the same figure are superimposed the headscarps of the landslides of Avignonet and Harmalière. Below the Avignonet slide, the ridge of compact layers continuously extends perpendicularly to the global slide motion and could act as a buttress. On the contrary, the Harmalière landslide clearly developed over the lower elevation zone (Figure 4) and its motion can be explained by the orientation of the Drac paleo-valley which changes from NS to NW-SE in the South.

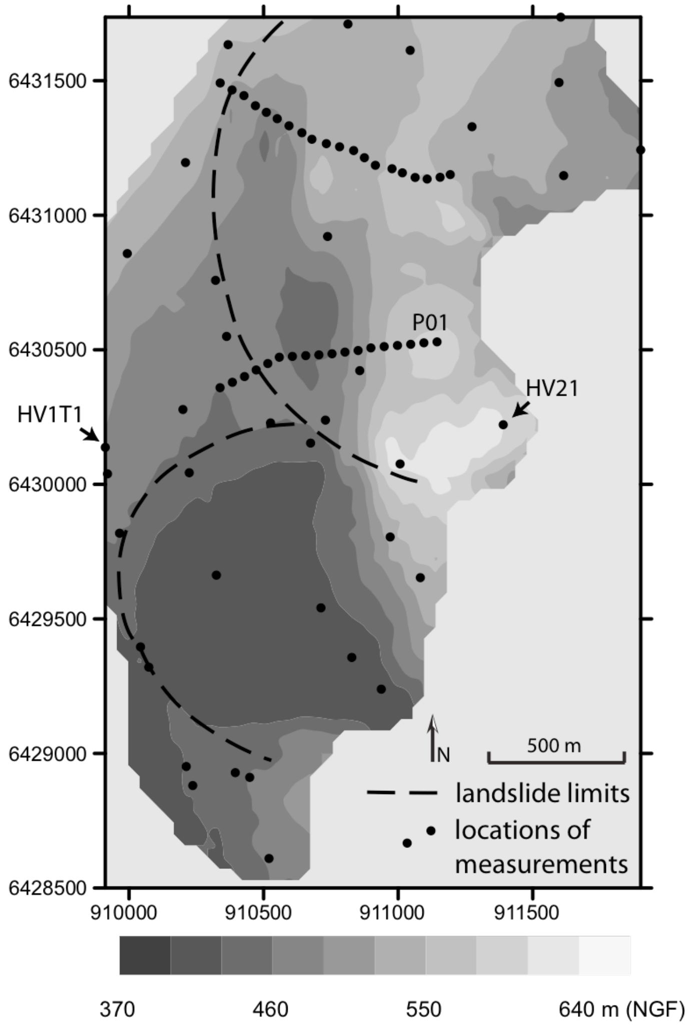

Figure 4. Paleo-topography of the bottom of the clay layer below the Avignonet and Harmalière landslides and locations of seismic noise measurements .

4 DISCUSSION / CONCLUSIONS

The presence of a buttress of hard formations (compact alluvial layers and bedrock) along the western shore of the lake was pointed out both by seismic data and geological observations. It probably prevents the development of a deep active slip surface at Avignonet. This geometry explains the higher displacement rates observed at the landslide toe, the clayey material being expelled over the rigid formations. This buttress disappears to the South, resulting from the presence of a paleo-valley of the river Drac shown by seismic data and alluvial layer outcrops. This paleo-valley, which allowed the deposit of thick clay layers, probably controlled the initiation and the unexpected Southeastward motion of the l'Harmalière landslide. The material eroded at the top is moving downward and feeds a funnel shaped track zone through which the material sediments and flows to the lake with a regular slope.

ACKNOWLEDGMENTS

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